Water Balance and Nitrate Leaching under Corn in Kura Clover Living Mulch

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Intercropping

ABSTRACT

Kura clover (*Trifolium ambiguum* M. Bieb.) living mulch has potential to improve the environmental impact of corn (*Zea mays* L.) production, especially in the context of corn silage or stover harvest. Our objective was to determine the effects of kura clover living mulch on the water balance and nitrate leaching under corn near Arlington, WI. Treatments in the 2.5-yr experiment (April 2006–November 2008) were N-fertilized no-till corn following killed kura clover as the control and no-till corn in living mulch with fertilizer rates of 0 and 90 kg N ha^{-1} yr^{-1}. Soil water storage was 37 to 50 mm lower under the living mulch than the control in the spring, while the control experienced 29 to 36 mm greater soil water depletion than the living mulch in the summer. Evapotranspiration was similar across treatments, except in May when it was greater under the living mulch by 11 to 41 mm. The living mulch did not appreciably reduce drainage. Nitrate-N storage in the soil profile and nitrate-N concentrations in the soil solution at 1-m depth were significantly reduced (p = 0.10) under both living mulch treatments relative to the control. Flow-weighted nitrate-N concentrations were 23 mg L^{-1} for the control, 17 mg L^{-1} for the living mulch with 90 kg N ha^{-1} yr^{-1}, and 6 mg L^{-1} for the living mulch with 0 kg N ha^{-1} yr^{-1}. Total nitrate-N leached was reduced 31 and 74% relative to the control under the living mulch with 90 and 0 kg N ha^{-1} yr^{-1}, respectively.

In the midwestern United States, corn production is a dominant land use. In 2008, approximately 15 million hectares of corn were planted in the four States of Illinois, Iowa, Minnesota, and Wisconsin, accounting for 46% of all cropland in those States (National Agricultural Statistics Service, 2009; Natural Resources Conservation Service, 2007). Corn yields in the region are high and increasing due to good soils and climate, improved hybrids, and expert management. Those corn yields support large industries such as livestock production and, increasingly, ethanol production. Corn-based cropping systems make this one of the most verdant agricultural regions in the world, for a few months each year.

For the remainder of the year, the fields are dormant, solar radiation is not captured for photosynthesis, soil organic carbon is lost to respiration, the soil surface is relatively unprotected, and nutrient-rich soil water is prone to leach out of the root zone. These problems are exacerbated when corn is harvested for silage or if stover is harvested for biofuel production or livestock feed (Blanco-Canqui and Lal, 2007; Dolan et al., 2006; Wilhelm et al., 2007). Wasted solar radiation, leached nutrients, and eroded soil are indicators that the production potential of the land is not being fully used. The resulting negative off-site impacts on groundwater, surface water, and atmospheric greenhouse gas concentrations are major environmental concerns. The agricultural systems of the region, to meet global resource needs and to be sustainable, must undergo a process of biological intensification.

Biological intensification is the process of intentionally increasing the number of species in an agricultural system. Biological intensification involves raising complementary species in beneficial spatial and temporal arrangements. Biological intensification is pursued with the intent: (i) to increase agricultural productivity per unit of land area, (ii) to conserve and improve the soil, and (iii) to create positive off-site impacts on water quality and greenhouse gas concentrations.

Living mulches may provide one path to effective biological intensification of agriculture. A living mulch is a cover crop grown "with a main crop and maintained as a living ground cover throughout the growing season" (Hartwig and Ammon, 2002). The benefits of living mulch cropping systems are multifaceted. Living mulches can reduce soil erosion and pesticide transport (Hall et al., 1984), improve soil quality (Jokela et al., 2009), and promote biological control of weeds and insect pests (Ilnicki and Enache, 1992; Prafsifka et al., 2006). Leguminous living mulches can also supply a portion of the N needs of a cereal crop through biological N fixation (Duiker and Hartwig, 2004).

Living mulches may reduce nitrate leaching under cereal crops. Liedgens et al. (2004b) found that nitrate leaching under corn near Zurich, Switzerland was reduced >95% by a mechanically suppressed (clipped) living mulch of Italian ryegrass (*Lolium multiflorum* Lam.), however corn yields were reduced

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Abbreviations: ET, evapotranspiration; MCL, maximum contanimant level; PSNT, presidedress soil nitrate test; TDR, time domain reflectometry.

Table 1. Physical properties of the Plano silt loam soil at the study site.

Layer	Organic matter†	Bulk density‡	Particle size analysis§ Sand	Silt	Clay	Soil water content at −33 kPa¶	Soil water content at −1500 kPa¶
cm	g kg^{-1}	Mg m^{-3}		%		m^3 m^{-3}	
0–25	38.9	1.53	16	64	20	0.41	0.19
25–50	23.8	1.56	13	61	26	0.40	0.19
50–75	18.9	1.60	11	60	28	0.39	0.20
75–100	15.9	1.72	16	60	24	0.36	0.17

† Loss on ignition method.

‡ 3.8 cm diam. core segments from hydraulic sampler.

§ Hydrometer method.

¶ Pedotransfer function of Rawls et al. (1992).

by approximately 50%. In that study, the Italian ryegrass was planted in the autumn with corn planted into a killed strip the following spring. However, more favorable results have been reported from studies in Quebec. Those studies found that when Italian ryegrass was planted 10 d after corn planting the living mulch reduced nitrate leaching by 50% (Kaluli et al., 1999) with no reduction in corn yield and a 2 to 3 Mg ha^{-1} increase in total biomass production (Zhou et al., 2000). These data suggest that graminoid living mulches can reduce nitrate leaching significantly, but no data are available to quantify the effects of leguminous living mulches on nitrate leaching.

Kura clover is a perennial, rhizomatous legume that is well suited as a living mulch for corn production in the midwestern United States. In Wisconsin, Zemenchik et al. (2000) found that kura clover living mulch provided year-round soil protection with little or no reduction in corn yield. Corn whole plant yield reduction averaged across 2 yr was 8%. Subsequently, Affeldt et al. (2004) found no significant reduction in whole plant or grain yield for herbicide-resistant corn in strongly suppressed kura clover. Kura clover is also compatible with other annual grass species for forage production. Binary mixtures of kura clover with winter wheat (*Triticum aestivum* L.) and winter rye (*Secale cereale* L.) have produced similar yields to monocultures of the grasses while producing forage of higher nutritive value (Contreras-Govea and Albrecht, 2005; Contreras-Govea et al., 2006).

One of the primary challenges with living mulch cropping systems is competition for water between the main crop and the living mulch. In Illinois, Kurtz et al. (1952) found that yield reductions from a variety of living mulches were 29% on average for nonirrigated corn but only 11% for irrigated corn. Similarly in Minnesota, Eberlein et al. (1992) found that suppressed alfalfa (*Medicago sativa* L.) living mulch reduced nonirrigated corn yield 20% on average but did not reduce the yield of irrigated corn. Despite these indications of water limitations, little is known about soil water balance under living mulches. Results from prior studies range from reduced soil water content only during an early season dry spell (Eberlein et al., 1992), to no effect on soil water content (Zemenchik et al., 2000), to higher soil water content under living mulch (Martin et al., 1999). Only one study has shown consistently lower soil water content under living mulch (Liedgens et al., 2004b), but the Italian ryegrass living mulch was not chemically suppressed in that study.

Our general objective is to learn whether corn grown in kura clover living mulch is a viable option for biological intensification of agriculture in the midwestern United States. The specific objective of this research was to determine the impact of a kura clover living mulch on the water balance and nitrate leaching under corn near Arlington, WI.

MATERIALS AND METHODS

Field studies were conducted from April 2006 through November 2008 at the University of Wisconsin Arlington Agricultural Research Station (43°18' N, 89°21' W, 310 m above sea level). Plots were located on a nearly level upland area on Plano silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiudolls). The Plano series is extensive, covering more than 1.7 × 10^5 ha in the Upper Midwest region of the United States. Most areas of Plano soils are cultivated (Natural Resources Conservation Service, 2008). Basic physical properties of the soil are given in Table 1. Kura clover (experimental line KTA202) had been established in the plot area in spring 2004 and mechanically harvested three times per season in the 2 yr before this experiment was initiated. The experiment was a randomized complete block design with four replications. The control was corn following a perennial legume and is comparable to corn following alfalfa, a common cropping system supporting dairy and beef production in the midwestern United States. The control was managed for no-till corn production with a nonlimiting N supply. Living mulch treatments were corn grown in band-killed, herbicide-suppressed kura clover with fertilizer N rates of 0, 22, 45, 60, and 90 kg N ha^{-1}. This treatment structure was designed to facilitate a concurrent experiment on the N response of corn grown in kura clover living mulch. To assess the impact of kura clover living mulch on the water balance and nitrate leaching under corn, the living mulch treatments receiving fertilizer N rates of 0 and 90 kg N ha^{-1} yr^{-1} were compared to the control. The plots for these three treatments were 6 m (eight rows) wide and 9.2 m long. The 0 and 90 kg N ha^{-1} rates were selected because resources were limited, and these rates were likely to produce the lowest and highest levels, respectively, of N leaching under the living mulch in this study. The same plots were used all three growing seasons.

Agronomic Management

Kura clover in the control was killed in April 2006 with a mixture of flumetsulam [N-(2,6-difluorophenyl)-5-methyl-1,2,4-triazolo-[1,5a]-pyrimidine-2-sulfonamide] (0.052 kg a.i. ha^{-1}), clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) (0.14 kg a.e. ha^{-1}), dicamba (3,6-dichloro-o-anisic acid) (0.28 kg a.e. ha^{-1}), and glyphosate [N-(phosphonomethyl) glycine] (1.26 kg a.e. ha^{-1}). Kura clover in the living mulch treatments received initial suppression with glyphosate (1.26 kg a.e. ha^{-1}) and dicamba (0.14 kg a.e. ha^{-1}) in the spring of 2006 when it was 8 to 10 cm tall. Corn was no-till planted between 25 and 30 April each year. A 20 cm wide band herbicide application at planting was used to kill kura clover directly over the corn row. This band herbicide application consisted of the same components and rates used in the broadcast mixture in the killed control, excluding glyphosate. A second broadcast application of glyphosate (1.26 kg a.e. ha^{-1}) was made to suppress kura clover and kill annual weeds approximately 5 wk after planting.

Nitrogen fertilizer additions to the control were selected to ensure that N was nonlimiting. This enabled the control to serve as a reference for the concurrent experiment examining the N response of corn in kura clover. There are currently no N management recommendations for corn following kura clover, thus decisions were made based on the available information for corn following other perennial legumes. To the first year corn following kura clover, 90 kg N ha^{-1} fertilizer was applied. Andraski and Bundy (2002) recommended using book value N credits or the presidedress soil nitrate test (PSNT) for first year corn following legumes. The book value N credit for red clover (*Trifolium pratense* L.) and birdsfoot trefoil (*Lotus corniculatus* L.) leads to a recommended N rate of 45 kg N ha^{-1} (Kelling et al., 1998). A survey of farmers in northeast Iowa found an average N application rate of 100 kg N ha^{-1} to first year corn following alfalfa (Rowden et al., 2001). Thus, the rate we selected was above the recommended rate but below what has been reported for farms in the region. For second year corn following legumes, the use of the PSNT is recommended (Andraski and Bundy, 2002). Applying the PSNT in the control plots resulted in a recommendation of no added N, however, 45 kg N ha^{-1} was applied to ensure that N was nonlimiting. The aforementioned farmer survey found an average N application rate to second year corn following alfalfa of 145 kg N ha^{-1}, far exceeding the rate we selected. In the third year, the use of the PSNT led to a recommendation of 179 kg N ha^{-1} for the corn in the control plots. This recommendation was followed. Totals for the three growing seasons were: 229 kg N ha^{-1} recommended, 314 kg N ha^{-1} applied, and 414 kg N ha^{-1} reported on-farm average for corn following alfalfa. Thus, the N input to the control was more than recommended and less than common practice. The 0 and 90 kg N ha^{-1} living mulch treatments received those rates each growing season. All N was side-dress applied as ammonium nitrate about 6 wk after planting.

Corn whole-plant and grain yields were collected from two of the internal rows each autumn. Whole-plant corn (as for silage) was hand harvested at about 50% kernel milk-line, which typically occurred around 15 September. Grain yields were determined by hand harvest approximately 10 October each year. Corn grain yield was adjusted to 155 g kg^{-1} moisture content. After grain harvest, all remaining corn was cut at about 15 cm stubble height, and the cut plants were removed from the field, simulating silage harvest or stover harvest.

Management practices were adapted to field conditions as needed. Spring development of kura clover is slower the year after corn production (Zemenchik et al., 2000), so aggressive early control was not necessary. In 2007, the initial broadcast suppression was delayed until 16 May, and the herbicide rates were 1.26 kg a.e. glyphosate ha^{-1} and 0.07 kg a.e. dicamba ha^{-1}. In 2008, the initial broadcast suppression was 19 May.

Water Balance Method

A water balance for the experiment was developed using a combination of measurements and modeling. Daily precipitation measurements (liquid and solid) were recorded by Research Station staff following National Weather Service Cooperative Observer protocols. The archived data (Cooperative Station no. 470308) were retrieved from the National Climatic Data Center website (National Climatic Data Center, 2008).

Soil water storage to 1 m depth was monitored daily by time domain reflectometry (TDR) (Topp and Ferré, 2002). Four 1-m long, PVC coated, TDR sensors were installed vertically in one replication of the control and the living mulch receiving 90 kg N ha^{-1} (a total of eight sensors). When the soil was moist, the two 1.3-cm diam. waveguides of each sensor were driven into the soil simultaneously using a hammer. A spacer was used to keep the waveguides parallel and spaced 8.8 cm apart during installation. The data acquisition system consisted of a datalogger (CR10X, Campell Scientific, Logan, UT), a coaxial multiplexer (SDMX50, Campbell Scientific, Logan, UT), and a time domain reflectometer (TDR100, Campbell Scientific, Logan, UT). The TDR waveforms were processed in MatLab (The MathWorks, Inc., Natick, MA) to determine the apparent dielectric permittivity of the soil. Corrections were applied for the effects of the PVC coating (Ferré et al., 1996). Water content was estimated from the apparent dielectric permittivity of the soil using the linear calibration equation of Ferré and Topp (2002). One tensiometer was installed in each plot at 1-m depth to provide supplemental data about soil moisture status. Tensiometer readings were recorded every 2 wk when the soil was not frozen using a pressure transducer and digital display.

Evapotranspiration (ET) was modeled using the FAO-56 dual crop coefficient method (Allen et al., 1998). In this method ET from a grass reference crop (ET_0) was calculated using the Penman–Monteith equation assuming a fixed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23. Daily air temperature, vapor pressure deficit, incoming solar radiation, and wind speed were obtained from the University of Wisconsin Automated Weather Observation Network site located at the Research Station (University of Wisconsin Extension, 2008). These daily weather variables were used to calculate ET_0. The actual ET is related to ET_0 by

$$ET = (K_s K_{cb} + K_e)\, ET_0 \qquad [1]$$

where K_s is the water stress coefficient, K_{cb} is the basal crop coefficient, and K_e is the coefficient for evaporation of water from exposed soil.

These three coefficients were calculated on a daily basis accounting for modeled temporal changes in plant development, soil surface water content, and root zone water content in accordance with the FAO-56 procedure. The values of K_{cb} for corn followed the course of crop development through the growing season using recommended values (Allen et al., 1998). Since K_{cb} values for kura clover have not been developed, recommended values for alfalfa were used instead. The kura clover K_{cb} values were reduced after herbicide suppressions in the manner recommended for alfalfa K_{cb} values after cutting. The value of K_s decreased linearly from 1 to 0 when the amount of water remaining in the root zone decreased below a soil

Table 2. Partial listing of parameter values used in the evapotranspiration calculations. All other parameters were as specified by Allen et al. (1998) with alfalfa parameters used for kura clover.

Parameter	Units	Control	Living mulch	Source
Residue cover in dormant season	%	10	90	estimated
Maximum root depth	m	1	1	Table 22, Allen et al. (1998)
Minimum root depth	m	0.2	0.2	p. 279, Allen et al. (1998)
Maximum height of kura clover	m		0.2	estimated
Daily depth of soil water frozen/thawed when maximum air temperature less/greater than 0°C	mm	1	1	estimated

and crop specific threshold value. The value of K_e was approximately 1.2 for fully exposed wet soil and decreased to 0 as soil cover increased and soil surface water content decreased. Water content of the surface soil layer is estimated on a daily time step within the dual-crop coefficient method. A partial list of the parameter values used in the ET calculation is given in Table 2. For the living mulch, daily K_{cb} was calculated independently for sole corn and sole kura clover and the larger of the two values was used. Further details of the FAO ET calculation method can be found in Allen et al. (1998).

The amount of water draining below the root zone (D) was estimated by

$$D = P - \mathrm{ET} - \Delta S \quad [2]$$

where P is precipitation and ΔS is change in soil water storage. All terms are expressed in millimeters. Runoff was negligible for these no-till plots on level ground with good internal drainage. Seasonal measurements of soil water storage and ΔS were obtained by soil sampling to 1-m depth at the start and end of the growing season. These soil sampling data were used to calculate drainage because the TDR data contained gaps and reported liquid water rather than total water. Thus, D was calculated for each of three growing seasons and the two intervening dormant seasons.

Nitrate Leaching Measurements

The nitrate-N concentration in the soil solution at 1-m depth was monitored using 4.8 cm o.d. ceramic suction cup samplers (Model 1920F1, Soilmoisture Equipment Corp., Santa Barbara, CA) in all replications of the control and the living mulch with 0 and 90 kg N ha^{-1}. The samplers were modified according to the method of Crabtree and Seaman (2005). These modifications include adding permanent sample extraction tubes, adding quick-connect fittings, and protecting the aboveground portions with a PVC casing. The samplers were installed vertically in boreholes created with a hand auger. The borehole diameters were approximately 2 cm larger than the outer diameter of the sampler. Silica flour slurry was placed in the bottom of the hole, and the sampler was embedded in the slurry. The annulus was then filled with native soil to within 20 cm of the soil surface. The remainder of the annulus was filled with bentonite slurry to prevent preferential flow down the annulus. Two samplers were installed 3 m apart in the central interrow area of each plot. Thus, there were eight samplers per treatment, a number selected based on consideration of prior similar studies (e.g., Lord and Shepherd, 1993) and available resources.

Soil water samples were collected every 2 wk when the soil was not frozen and the soil water content was sufficient to permit water collection. To collect water samples, a vacuum of −60 kPa was applied to the samplers for a period of 24 h. The vacuum was then released and all the accumulated water was removed into 250-mL polyethylene bottles. The water samples were frozen until analysis. When the samples were thawed, the volume of each sample was determined. Nitrate-N concentrations were measured by flow injection analysis (Model QC8500, Lachat Instruments, Milwaukee, WI) using the colorimetric Cd reduction method. The concentrations include nitrite-N which was assumed to be negligible (Zhu and Fox, 2003). The mean sample volume was 147 mL and the within sampling date, within treatment, coefficient of variation averaged 79%. For nitrate N concentration, the within sampling date, within treatment, coefficient of variation averaged 48%.

Drainage under a given treatment was considered unlikely on sampling dates when fewer than half of the samplers in that treatment yielded a water sample (Lord and Shepherd, 1993). For those cases, the measured nitrate-N concentrations were not included in any subsequent calculations. For every other sampling date, a weighted average of the measured nitrate-N concentrations from the two samplers in each plot was calculated based on the volume of water collected. Monthly average nitrate N concentrations were then calculated for each treatment. Seasonal nitrate N leaching loads at 1-m depth were calculated as the product of the seasonal drainage total and the average monthly nitrate-N concentrations during the season.

Soil Sampling

Soil water content, bulk density, and nitrate-N storage were measured by soil sampling at the beginning and end of each growing season. Six soil cores approximately 3.8 cm in diameter and 100 cm in depth were collected in each plot of the control and the living mulch with 0 and 90 kg N ha^{-1} using a truck-mounted hydraulic sampler. The cores were cut into 25-cm segments, and a subsample of each segment was dried at 105°C to determine soil water content and bulk density. The remainder of the soil was air-dried at ~40°C, ground to <2 mm, and stored for analysis. Subsamples of 15 g were shaken in 30 mL of 0.05 M K_2SO_4 for 0.5 h and the extracts were filtered (Whatman no. 1). Filtrate samples were analyzed for the sum of nitrite-N and nitrate-N by flow injection analysis.

RESULTS AND DISCUSSION

Environment

For analysis and discussion, we divided the experiment into 6-mo periods approximating the growing season (April–September) and the dormant season (October–March). For the period of the experiment, 96% of the cumulative base 10°C growing degree days occurred during the growing season thus classified (Table 3). The experiment was marked by above average precipitation in general (Fig. 1). In fact, the period from December 2007 through May 2008 was the second wettest on record for the upper

Mississippi River basin (Dirmeyer and Brubaker, 2009). However, April through July was dry in 2007 with cumulative precipitation 105 mm (or 28%) below the 30 yr average. A similar or greater precipitation deficit for April through July occurred only three times in the previous 30 yr at this site, and the most recent prior occurrence was in 1989. Also, July through September was dry in 2008 with cumulative precipitation 90 mm (30%) below average.

Yields

The control produced high yields of both whole plant dry matter (18.0–21.9 Mg ha^{-1}) and grain (13.8–15.3 Mg ha^{-1}). Yields were generally lower in the living mulch treatments than in the control. For the living mulch receiving 90 kg N ha^{-1} annually, yields were reduced 14% on average relative to the control. This result differs from a previous study which found no yield reduction for a similarly managed living mulch system (Affeldt et al., 2004). Whole plant and grain yields for the living mulch with 90 kg N ha^{-1} were lowest in 2007. Water stress resulting from the April through July dry period is a likely explanation that will be considered in more detail below. For the living mulch with no added N, the average yield reduction relative to the control was 30%. A complete analysis of the corn yields from this experiment is reserved for a future manuscript.

Soil Water Content

Soil water contents measured by the TDR sensors were on average 0.01 m^3 m^{-3} higher under the living mulch than in the control (Fig. 2). This small mean difference could be due to a reduction in evaporation by the living mulch, to spatial variability, or to measurement error. The difference is consistent with the results of Martin et al. (1999) who also found higher soil water contents under living mulch. The water contents determined from seasonal soil sampling of all plots to 1 m depth validated the accuracy and representativeness of the TDR data (Fig. 2). Data for 2006 from the TDR sensors were not available due to equipment malfunction.

The lower liquid water content for the control compared to the living mulch from December 2007 through March 2008 likely reflects deeper frost penetration under the control. Averaged across all 3 yr, the soil water content to 1-m depth was 0.40 m^3 m^{-3} at the beginning of the growing season for both the control and the living mulch. This compares well with 0.39 m^3 m^{-3}, the water content at –33 kPa estimated using the regression equation of Rawls et al. (1992). Thus, both the control and the living mulch treatments entered the growing seasons at "field capacity" with no soil water deficit carried over from the prior year.

In 2007, greater early growing season transpiration led to lower soil water contents in the living mulch relative to the control beginning 9 May (Fig. 2). The largest measured deficit was 50 mm on 19 June. The effects of the living mulch extended to a depth of 1 m where the average matric potentials on 8 June were –4 kPa for the control compared to –36 and –41 kPa for the living mulch with 0 and 90 kg N ha^{-1}, respectively. Matric potential in the control remained above –40 kPa until 20 July. In May 2008, the living mulch also depleted soil water content beginning about 17 May, reaching a maximum soil water deficit of 37 mm less than the control on 30 May. Again, the effects of early season water use by the kura clover were evident even at 1-m depth where the average matric potentials on 28 May were –5 kPa for the control compared to –16 and –24 kPa for the living mulch with 0 and 90 kg N ha^{-1}, respectively. Unlike in 2007, these effects were soon negated by heavy rain in June. Similar temporary soil water depletions by living mulch were observed by Eberlein et al. (1992). They reported depletions reaching 32 mm in the top 46 cm of the soil profile for partially-suppressed alfalfa living mulch. The TDR and tensiometer data suggest that the living mulch increases the probability of corn experiencing water stress, especially when the late spring is drier than average. The magnitude of the increased risk remains to be quantified and will likely be site specific.

Later in the growing season, at the time of maximum soil water depletion, soil water content was lower under the control. This was evident in both 2007 (36 mm difference on 3 August) and 2008 (29 mm difference on 12 September). At these times the corn canopies were dense, and transpiration by the corn likely accounted for most of the water depletion. Thus, we hypothesize that the living mulch reduced or delayed the development of the corn root system to some extent thereby reducing the corn's ability to deplete soil water stores. Reduced belowground corn biomass would be consistent with the reduced corn yields under the living mulch treatments, assuming similar root/shoot ratios for corn in each treatment. Others have postulated that the inability of corn plants to establish a competitive root system in a living mulch is a key factor limiting growth and yield (Liedgens et al., 2004a).

Evapotranspiration

The control and living mulch systems exhibit differing seasonal ET dynamics. These differences are partially reflected in the modeled K_{cb} values shown in Fig. 3. The perennial kura

Table 3. Weather summary for three growing seasons (GS 1, 2, and 3) and two dormant seasons (DS 1 and 2). Growing degree days are calculated with base of 10°C.

Season	Precipitation	Solar radiation	Growing degree days
	mm	MJ m–2	°C d
GS 1	751	2882	1238
DS 1	252	1427	52
GS 2	607	3510	1323
DS 2	346	1565	101
GS 3	819	3348	1153

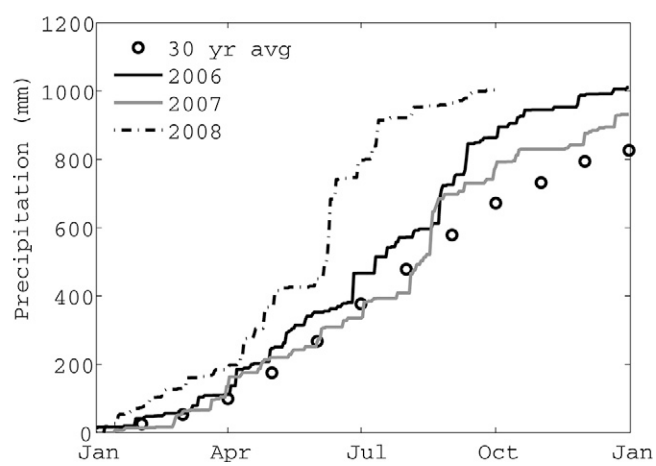

Fig. 1. Precipitation patterns for the three calendar years encompassing the experiment along with the 30-yr average precipitation for the site.

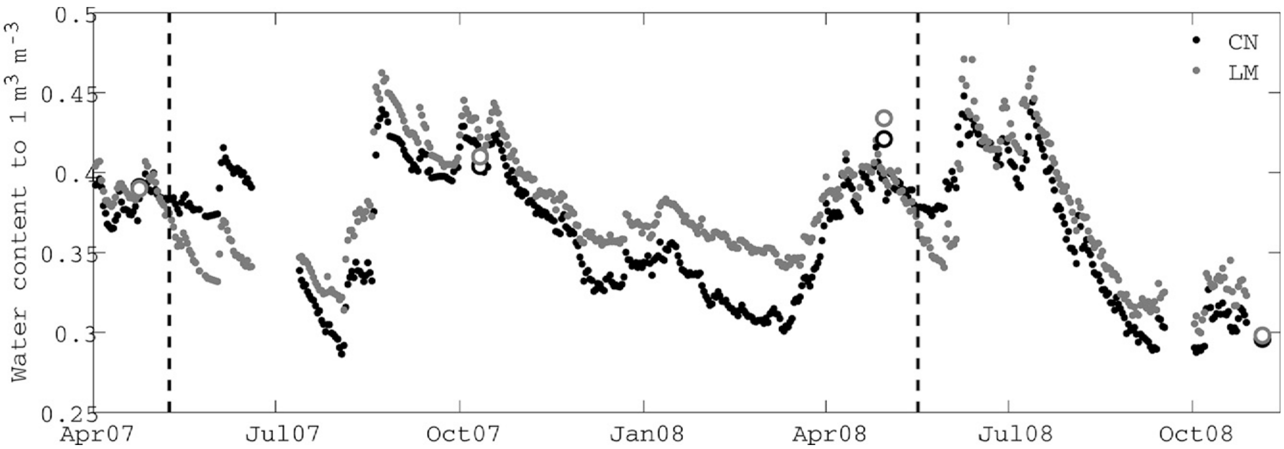

Fig. 2. Average time domain reflectometry (TDR) measured liquid soil water content to 1-m depth under control (CN) and living mulch (LM). Open circles represent direct measurements of soil water content from soil sampling. Dashed vertical lines at 9 May 2007 and 17 May 2008 mark the beginning of spring soil water depletion by the living mulch.

clover initiates transpiration earlier in the growing season than the corn. However, the transpiration of the kura clover is curtailed periodically by herbicide suppressions. The successive growth and suppression cycles are represented by the early season ramps and abrupt cutoffs in the living mulch K_{cb} values. By early June, transpiration from the corn begins to accelerate as the corn canopy increases in height and leaf area. By mid-June, K_{cb} for the corn equals or exceeds K_{cb} for the kura clover. As the corn approaches maturity, its green leaf area begins to decline, initiating a downward trend in K_{cb} and transpiration. The kura clover, in contrast, maintains green leaf area later in the year, creating a 50 to 60 d window where K_{cb} and transpiration of the living mulch is greater than that of the control. Notably, this greater late season K_{cb} for the living mulch is offset by a lower late season evaporation coefficient, K_e, relative to the control (data not shown). This means that ET should be similar for the living mulch and control treatments late in the growing season, and late season transpiration by the kura clover should not reduce soil water availability for the next crop. The soil water content data (Fig. 2) are in agreement with these expectations.

Water stress can play an important role in the ET process, even in this humid climate. The ET model predicted some reductions in transpiration due to water stress in each growing season for both the control and the living mulch (data not shown). In 2006 and 2008, the modeled water stress began in about mid-August and was unlikely to significantly affect yields. In 2007, the modeled water stress began in late June for the living mulch and mid-July for the control. Corn grain yields are most sensitive to water stress during silking (Claassen and Shaw, 1970), which occurred in the second half of July for the living mulch treatment. The average modeled water stress coefficient, K_s, during this time period of 2007 was 0.39 indicating a 61% reduction in transpiration. In contrast, silking in the control occurred in the first half of July, before the onset of water stress ($K_s \cong 0.99$). Thus, in 2007, the living mulch both increased the water stress experienced by the corn and delayed the corn development so that the water stress occurred at a more damaging time. Others have reported similar delays in corn development due to the presence of a living mulch (Martin et al., 1999).

The monthly ET was remarkably similar for the control and the living mulch systems, despite the drastic differences in vegetative cover (Fig. 4). The notable exception was the month of May when the modeled ET for the living mulch was consistently greater (11–41 mm) than that for the control. The increased May ET in the living mulch system was inversely related to the May precipitation. When May was wet (e.g., 2006) ET differed little from the control, but when May was dry (e.g., 2007), living mulch ET was much greater than that from the control. Modeled ET for July 2007 was 46 mm lower for the living mulch than the control, a negative consequence of the greater living mulch ET in May.

Independent estimates of the growing season ET for the control can be obtained using literature values for ET efficiency. The ET efficiency is here defined as the mass of grain produced per unit area per mm of growing season ET. Tanner and Sinclair (1983) measured an evapotranspiration efficiency of 24 kg ha^{-1} mm^{-1} for corn at this Research Station. Dividing measured grain yields by this value produces evapotranspiration estimates of 638, 604, and 575 mm for the three growing seasons in this study. These values are 4% less than the estimates from the FAO-56 dual crop coefficient method (Table 4). This close agreement provides a measure of independent support for our results.

Drainage

The kura clover living mulch did not appreciably reduce the amount of drainage below the root zone (Table 4). Estimated drainage totals over 30 mo were 645 mm for the control and 623 mm for the living mulch. This similarity may seem surprising, but we hypothesize that during wet periods, evaporation from the dark, exposed soil surface of the control may be similar in magnitude to transpiration from the kura clover. Similar results were reported by Kaluli et al. (1999) who found no significant difference between tile drain flow from corn with or without intercropped ryegrass in Quebec. In contrast, Liedgens et al. (2004b) found deep drainage under corn in Switzerland was reduced approximately 40% by the presence of a mechanically suppressed Italian ryegrass mulch. Such large reductions in drainage may not be achievable with chemically suppressed living mulches.

Drainage totals differed by <14 mm between the control and living mulch in each of the three growing seasons (Table 4). Larger differences occurred during the dormant seasons. During the first dormant season, drainage under the living mulch was

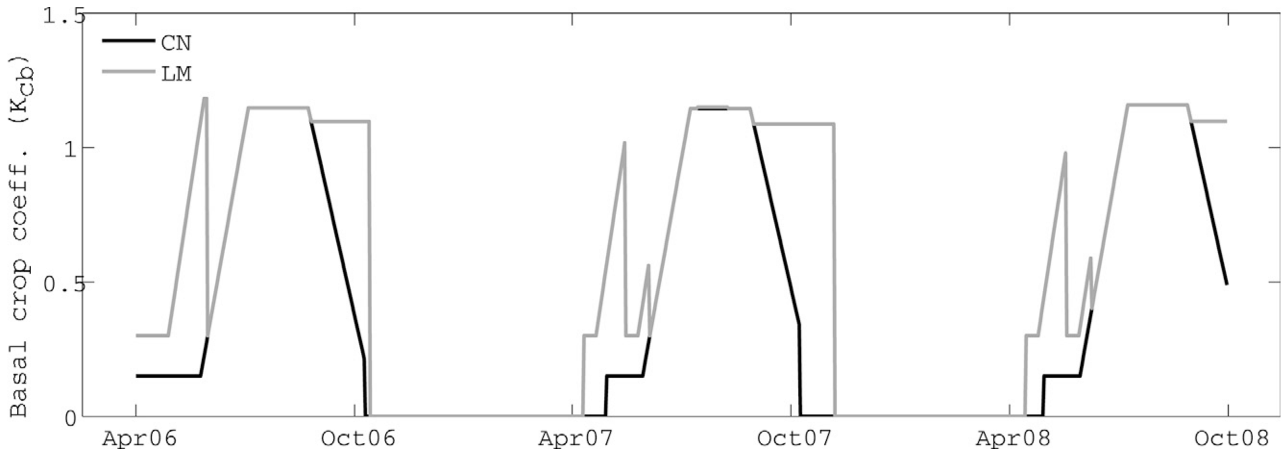

Fig. 3. Control (CN) and living mulch (LM) time series of basal crop coefficients modeled according to the FAO-56 method.

26 mm greater than under the control. In contrast, drainage under the living mulch was 31 mm less than the control during the second dormant season. Earlier onset of cold temperatures in the first dormant season than the second led to earlier prediction of dormancy (i.e., $K_{cb} = 0$) in the kura clover (Fig. 3). Dormant clover does not transpire but rather shades the soil surface and reduces evaporation relative to the control. This contributed to the greater drainage under the living mulch in the first dormant season. The pattern was reversed in the second dormant season when cold temperatures occurred later, delaying dormancy, and permitting greater transpiration from the living mulch.

The calculated drainage amounts for this study are similar to those reported in prior studies at the same research station. Brye et al. (2000), using equilibrium tension lysimeters, measured 563 mm of drainage over a 30-mo period under no-till corn. That total is 10 to 13% less than our calculated drainage totals. Over a period of almost 4 yr, Brye et al. (2001) measured an average drainage rate of 306 mm yr^{-1} under no-till corn. That rate is 19 to 23% greater than our calculated drainage rates of 258 and 249 mm yr^{-1} for the control and living mulch, respectively. Thus, our calculated drainage rates are within the range of typical drainage rates for this location.

Drainage represented 23 and 22% of precipitation in the control and living mulch treatments, respectively. These drainage percentages are within the range observed in prior studies within this geographic region. For example, Brye et al. (2000) found drainage under no-till corn to be 31% of precipitation. Kanwar et al. (1997) found subsurface tile drain flow under continuous no-till corn to be 27% of annual precipitation in northeast Iowa. A 6-yr study in southwest Minnesota found subsurface tile drain flow under continuous corn to be 18% of precipitation (Randall et al., 1997).

Nitrate-Nitrogen Concentrations in Soil Solution at 1-m Depth

Nitrate-N concentrations in the soil solution at 1-m depth were significantly reduced ($p = 0.10$) in both living mulch treatments relative to the control (Fig. 5). Mean monthly nitrate-N concentration in the control increased steadily from background concentrations at the beginning of the experiment to a peak of 56 mg L^{-1} in June 2007. This trend was likely the result of mineralization of the killed kura clover combined

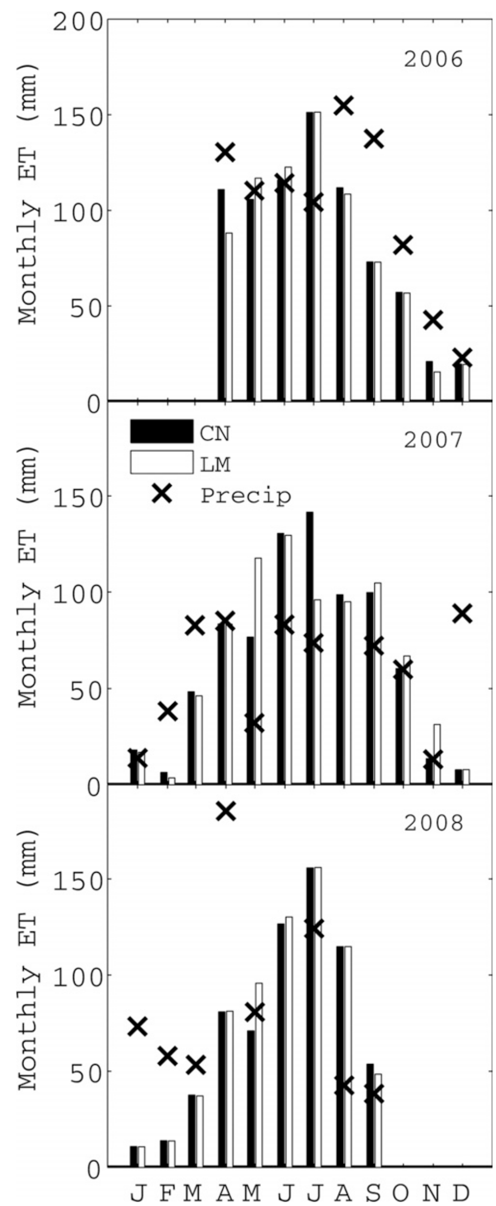

Fig. 4. Monthly evapotranspiration (ET) estimates for control (black bars) and living mulch (white bars) for the duration of the experiment. Monthly precipitation totals (X) are also plotted. Two monthly precipitation totals exceeded the plotted scale: 288 mm were received in August 2007 and 347 mm in June 2008.

Table 4. Water balance components for the control and living mulch for three growing seasons (GS 1, 2, and 3) and two dormant seasons (DS 1 and 2). No differentiation is made between the two living mulch treatments (0 and 90 kg N ha^{-1}) because the ET estimates are the same for each.

Season	*P*†	ET‡	Δ*S*§	*D*¶
	mm			
		Control		
GS 1	751	666	31	54
DS 1	252	170	−13	95
GS 2	607	626	13	−32
DS 2	346	144	17	186
GS 3	819	602	−125	342
		Living Mulch		
GS 1	751	658	42	51
DS 1	252	157	−27	121
GS 2	607	621	20	−34
DS 2	346	167	24	155
GS 3	819	626	−136	329

† *P*, precipitation.

‡ ET, evapotranspiration.

§ Δ*S*, change in soil water storage to 1 m depth.

¶ *D*, net soil water flow at 1 m depth (positive down).

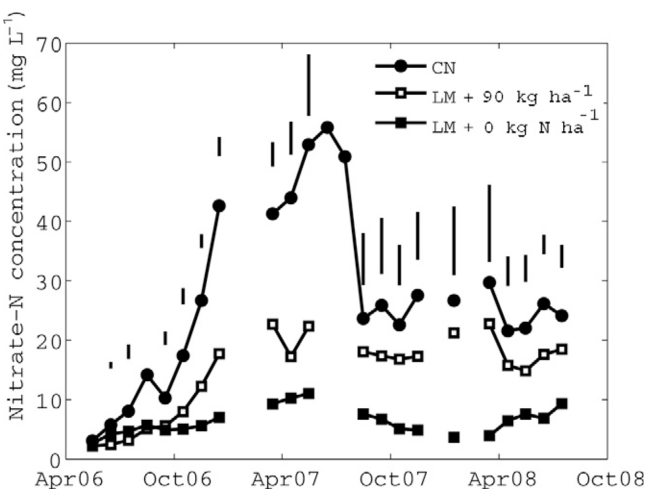

Fig. 5. Monthly mean nitrate-N concentration in soil solution samples at 1 m depth for the control (CN) and two living mulch (LM) treatments. Vertical bars above the data series indicate the least significant difference (*p* = 0.10). Absence of vertical bars indicates no significant differences occurred.

with the addition of N fertilizer. Similarly, Robbins and Carter (1980) observed soil solution nitrate N concentrations rising from background levels of <5 mg L^{-1} to a peak of 64 mg L^{-1} through the first 2 yr of N-fertilized corn following killed alfalfa. The control in our study represents corn following a perennial legume, a common type of crop rotation in the U.S. Midwest. The effects of mineralization would likely be less in rotations that do not include a killed perennial legume.

Following the peak in June 2007, nitrate N beneath the control declined sharply and stabilized between 22 and 30 mg L^{-1}, a comparable range to that observed in previous studies with continuous corn (Brye et al., 2001; Kanwar et al., 1997; Randall and Iragavarapu, 1995; Randall et al., 1997). In April through July 2008, long after the effects of mineralization had dissipated, nitrate-N concentrations under the control were still significantly higher than under the living mulch with 90 kg N ha^{-1}. For most of the experiment, nitrate concentrations under the control exceeded 10 mg N L^{-1}, the maximum contaminant level (MCL) for drinking water set by the USEPA.

The living mulch with no added N maintained nitrate-N concentrations below 10 mg L^{-1} for most of the experiment (Fig. 5). These data show that corn may be grown for three consecutive years in kura clover living mulch with no added N while maintaining low nitrate levels in water draining beneath the root zone. The observed concentrations were somewhat higher than the 3 to 4 mg L^{-1} observed under alfalfa in prior studies (Randall et al., 1997; Toth and Fox, 1998). Likewise, lower nitrate concentrations, ranging from 0 to 2 mg N L^{-1}, have been observed under corn with no added N (Kaluli et al., 1999; Zhu and Fox, 2003). These observations may indicate some asynchrony between plant N uptake and the rate of N mineralization from dead kura clover (whether killed by herbicides or by competition and shading by corn).

The living mulch with 90 kg N ha^{-1} exhibited nitrate N concentrations intermediate to the control and the living mulch with no added N, as expected. Nitrate-N concentrations in the soil solution at 1 m depth increased through the first year of the experiment before stabilizing around 20 mg L^{-1} (Fig. 5), thus this level of N addition is too large to meet the MCL target at this site. Prior studies have found 45 kg N ha^{-1} to be adequate for the living mulch system (Affeldt et al., 2004). Whether or not the MCL target is achieved for corn in kura clover living mulch receiving 45 kg N ha^{-1} is a question for future research.

Nitrate-Nitrogen Leached below the 1-m Depth

The total nitrate-N leaching under the living mulch with no added N was reduced 74% relative to the control, and the total nitrate-N leaching under the living mulch with 90 kg N ha^{-1} was reduced 31% relative to the control (Table 5). Since drainage amounts were similar across treatments, these large reductions are due primarily to lower nitrate-N concentrations beneath the living mulch. The impact of N mineralization on the nitrate-N loads was small because 80% of the total drainage occurred after 1 Oct. 2007 (Table 4) when the nitrate-N concentrations in the control had stabilized (Fig. 5). Considering only the data from 1 Oct. 2007 onward, the reductions in nitrate-N leaching relative to the control are 75% for the living mulch with no added N and 28% for the living mulch with 90 kg N ha^{-1}.

The observed leaching total for the control corresponds to an annual nitrate-N leaching loss of 60 kg N ha^{-1}. This is similar to the results of other studies in this region which have found annual nitrate-N leaching under no-till continuous corn ranging from 41 to 57 kg N ha^{-1} (Brye et al., 2001; Kanwar et al., 1997; Randall and Iragavarapu, 1995). In Michigan, Basso and Ritchie (2005) found an average total of 142 kg ha^{-1} nitrate N leached during 3

Table 5. Nitrate-N leached for three growing seasons (GS 1, 2, and 3) and two dormant seasons (DS 1 and 2).

Treatment	Season					Total
	GS 1	DS 1	GS 2	DS 2	GS 3	
	kg N ha^{-1}					
Control	4	31	−13	50	80	151
Living mulch + 90 kg N ha^{-1}	2	14	−6	36	57	104
Living mulch + 0 N	2	8	−3	7	25	39

yr of N-fertilized corn following alfalfa, which is similar to the 151 kg N ha^{-1} total in this 2.5 yr study (Table 5). Nitrogen fertilizer rates in these earlier studies ranged from 120 to 200 kg N ha^{-1} yr^{-1}.

The negative value for nitrate-N leaching during the 2007 growing season (Table 5) results from the estimated net water flow at 1 m being upward (i.e., negative) during that season (Table 2). This would be the natural result of root water uptake from below 1 m depth exceeding drainage from above 1 m depth. It is well established that in dry conditions corn roots can take up water at depths below 1 m (Allmaras et al., 1975). Statistical inferences about the nitrate-N load calculations in Table 5 are not warranted. These data are the product of replicated nitrate-N concentration measurements and modeled (consequently unreplicated) drainage estimates. There is one drainage estimate for each season applied to the four control plots and a different drainage estimate for each season applied to the eight living mulch plots (Table 4).

Flow-weighted nitrate-N concentrations for each treatment can be estimated by dividing the total leaching load by the total drainage. This gives average flow-weighted nitrate-N concentrations of 23 mg L^{-1} for the control, 17 mg L^{-1} for the living mulch with 90 kg N ha^{-1}, and 6 mg L^{-1} for the living mulch with no added N.

Soil Nitrate-Nitrogen

The measured soil nitrate-N concentrations provide some additional insights into the differing N cycle dynamics occurring in these treatments. The initial soil sampling (May 2006) revealed low soil nitrate-N concentrations <2 mg kg^{-1} at depths >25 cm in all treatments following 2 yr of pre-experiment kura clover production and forage removal (Fig. 6). There were no significant differences in soil nitrate-N concentration between treatments at any depth at the beginning of the experiment. Soil nitrate-N concentrations increased in all treatments during the first growing season, with the largest increases near the surface (Fig. 6, October 2006 data). These increases likely resulted from N fertilizer inputs and mineralization of killed kura clover which exceeded plant uptake. Recall that there was complete kura clover kill in the control and band-kill in the living mulch treatments. Suppression by glyphosate and shading by corn likely also caused root, nodule, and leaf death, providing additional substrates for mineralization. By the end of the first growing season, soil nitrate N was significantly higher in the 0- to 75-cm depth range under the control than under either living mulch treatment.

Over the first dormant season, soil nitrate-N concentration increased at depths >50 cm in all treatments (Fig. 6, April 2007 data). These increases likely result from continued mineralization of the killed kura clover and transport of nitrate N from the surface to the deeper layers. In contrast, the decrease of soil nitrate-N concentrations from October 2007 to April 2008 occurred primarily above the 25 cm depth (Fig. 6, April 2008 data). These decreases likely resulted from leaching in the control and from the combination of leaching and plant uptake in the living mulch treatments. We infer that the rate of mineralization of the killed kura clover was much less in the second dormant season than in the first. At the end of the experiment in November 2008, soil nitrate N was significantly higher for all depths under the control compared to the living mulch treatments.

Total soil nitrate N storage to 1 m was significantly reduced ($p = 0.10$) in both living mulch treatments relative to the control (Fig. 7.) The amount of residual soil nitrate N at the

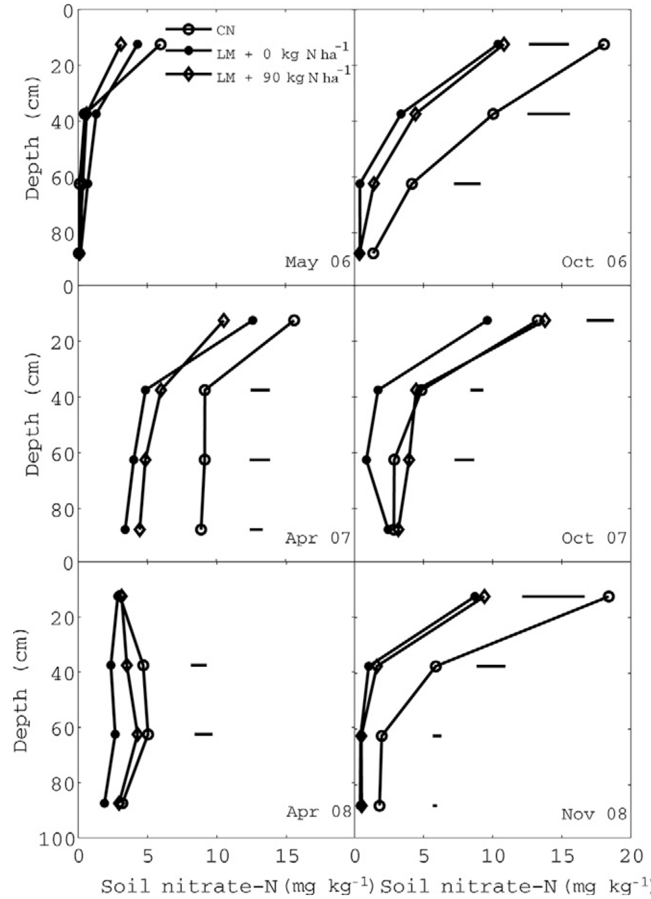

Fig. 6. Concentration of soil nitrate N vs. depth for the control (CN) and two living mulch (LM) treatments at the beginning and end of each growing season. Horizontal bars beside the data series indicate the least significant difference ($p = 0.10$). Absence of horizontal bars indicates no significant differences occurred.

end of the growing season can serve as a predictor for nitrate-N concentration in the leachate the following year (Randall and Iragavarapu, 1995). The residual soil nitrate-N levels were significantly reduced under the living mulch with no added N compared to the control, with an average reduction of 52%.

The living mulch with 90 kg N ha^{-1} also significantly reduced residual soil nitrate N in two out of three growing seasons relative to the control. The exception was after the 2007 growing season when the control received only 45 kg N ha^{-1} and drought stress limited corn N uptake in the living mulch. This was also the only instance when residual soil nitrate-N levels differed significantly between the two living mulch treatments. Across three seasons the residual soil nitrate N for the living mulch with 90 kg N ha^{-1} was reduced 33% on average relative to the control, consistent with the observed 31% reduction in nitrate N leaching. Residual soil nitrate N at the end of the experiment was significantly higher in the control than in either living mulch treatment, thus the pattern of greater nitrate-N leaching under the control would likely continue in the next season.

CONCLUSIONS

The impacts of kura clover on the soil water balance under corn were generally small, but temporary soil water depletion occurred under the living mulch during the spring and contributed to subsequent water stress in the corn. The living mulch treatments resulted in important water quality benefits, reducing nitrate-N leaching

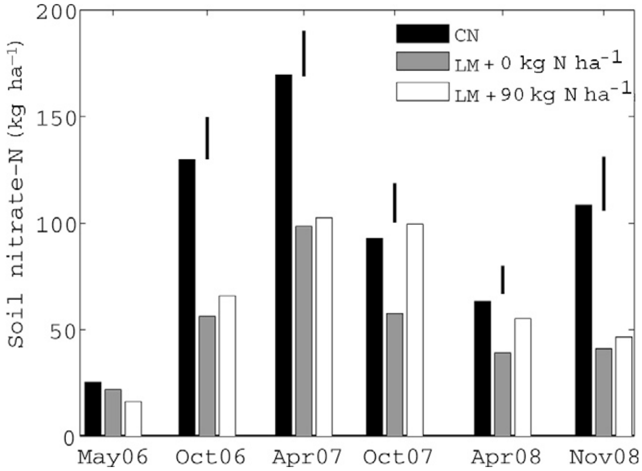

Fig. 7. Nitrate-N storage in the soil profile to 1 m depth for the control (CN) and two living mulch (LM) treatments. The vertical bars above the data series indicate the least significant difference (*p* = 0.10). Absence of vertical bars indicates no significant differences occurred.

31 to 74% relative to the control. The living mulch also provided valuable soil cover in this corn production system where both the grain and stover were harvested. Thus, the living mulch system has potential to improve the sustainability of whole plant corn harvest, whether for livestock feed or for bioenergy. Corn yields were reduced in the living mulch systems, and thus only two of the three objectives of biological intensification were achieved. Harvesting or grazing the kura clover or accounting for the value of the biological N fixation might improve the agricultural and economic productivity. Future work should consider these possibilities. More research is also needed on other aspects of the kura clover living mulch system including soil carbon effects, greenhouse gas emissions, and suitable crop rotations. In this living mulch experiment, biological intensification produced important environmental benefits but the potential economic losses due to yield reductions cannot be ignored.

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